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FACILITATING INFORMATION EXCHANGE FOR 3D RETROFIT MODELS OF EXISTING ASSETS USING SEMANTIC WEB TECHNOLOGIES

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Abstract: *Building Information Modelling (BIM) has gained a lot of momentum in new building projects in Architecture, Engineering, and Construction (AEC) for varying purposes like design, construction as well as Asset/Facilities Management (AM/FM). However, its use in existing buildings has been hampered by the challenges surrounding the limitations of available technologies used for generating retrofit models. In recent years, 3D laser scanning technology, as a remote sensing technique, has been extensively used to collect geometrical data from existing buildings. The output of this technology is a set of three-dimensional point measurements, also known as Point Cloud Data (PCD). In current practice, PCD is analysed and processed manually to generate BIM models utilising commercial BIM-driven platforms. Accordingly, several studies have been undertaken, proposing semi-automated approaches for generating parametric models by using PCD as the primary geometrical data source. An appropriate 3D model that is fit for purpose for a BIM-based process of design, construction, as well as operation and maintenance (O&M) of assets should incorporate geometrical and non-geometrical data. While the geometrical data can be extracted from the collected data, non-geometrical data may need to be appended to this for generating a genuinely semantically rich BIM model. On the other hand, a reliable data exchange framework could be beneficial within the AEC industry for O&M purposes. In this regard, a data exchange framework structured based on the Linked Data principles could be promising for creating a unified data format which would enhance the process of data exchange accordingly. This paper first outlines a framework proposed for generating semantically enriched 3D retrofit models for existing buildings by utilising the Resource Description Framework (RDF). RDF is utilised as a unified data format in the proposed framework to aggregate data captured from distributed offline and online data sources. The model, containing geometrical and non-geometrical data, is then generated through the conversion of RDF into IFC data model. However, the main focus of this paper is to propose a data exchange framework for populating the RDF data generated through the previously mentioned approach by using existing linked data schemas and vocabularies, such as Web Ontology Language for ifc (ifcOWL), Building Ontology Topology (BOT), Ontology for Managing Geometry (OMG), etc.*

KEYWORDS: *Building Information Modelling (BIM), Point Cloud Data (PCD), Information Exchange, Semantic Web Technologies, Resource Description Framework (RDF), Industry Foundation Classes (IFC), Web Ontology Language (OWL).*

1. Introduction and Background

The use of BIM process has lately gained a lot of momentum within the Architecture, Engineering, and Construction (AEC) (Volk, Stengel, & Schultmann, 2014). In the construction industry, BIM process has been utilised for various purposes, such as Asset/Facilities Management (AM/FM), renovation, and heritage restoration and preservation (Volk et al., 2014; Barazzetti, 2016). The use of BIM process is beneficial for improving different aspects of a building's life-cycle, such as the decision-making process and the precision of the design during the planning stage, quality of the product, management and exchange of information, energy efficiency, sustainability, and health and safety (Hayne, Kumar, & Hare, 2014; Sadeghineko, Kumar, & Chan, 2018). BIM models are one of the essential subsections of the BIM process. The information embedded in BIM models is used throughout a BIM-enabled asset life-cycle to facilitate the performance of Operation and Maintenance (O&M) (Klein, Li, & Becerik-Gerber, 2012), exchange of information about a facility (Tang, Huber, Akinci, Lipman, & Lytle, 2010), and energy analysis and simulation (Wang, Cho, & Kim, 2015). BIM models are also used to facilitate the design visualisation of an asset, estimation of material and cost, monitoring the condition of an asset, integration of design and fabrication, and incorporating supplementary information and knowledge into BIM models. Moreover, the exchange – storing, sharing, and reusing – of information embedded in BIM models is vitally crucial for taking full advantage of models in BIM-driven projects (Kumar, 2016).

While the use of BIM has gained a lot of interest in new building projects, its use in existing and retrofit buildings has been hampered by the challenges and limitations of related technologies (Barazzetti, 2016; Thomson & Boehm, 2015). Different data collection techniques, such as image-based (e.g. Photogrammetry and Videogrammetry) and range-based (e.g. 3D Laser Scanning) surveying technologies, are utilised to collect the data of an asset in the form of images and three-dimensional point measurements also known as Point Cloud Data (PCD) (Oliver, Seyedzadeh, Rahimian, Dawood, & Rodriguez, 2020). 3D laser scanning technology has been extensively used to collect geometrical data from existing buildings, and PCD is the output of this technology. PCD is used for various purposes like tracking & monitoring construction progress, capturing the actual as-built condition of a facility, health and safety on construction sites, energy efficiency, and generating parametric 3D models (Pour Rahimian, Seyedzadeh, Oliver, Rodriguez, & Dawood, 2020; Hayne et al., 2014; Seyedzadeh, Rahimian, Oliver, Glesk, & Kumar, 2020).

In current practice, PCD is used to generate building geometries in BIM-driven platforms manually, which is considered as a time-consuming, tedious, labour intensive, and error-prone process (Son & Kim, 2016). Hence, several studies have been carried out to develop and propose approaches for changing the manual process of generating BIM models into an automated or semi-automated process by utilising PCD as the primary geometrical data source (Thomson & Boehm, 2015). This process is also known as Scan-to-BIMs method. Technically, the result of such approaches is not a full-blown BIM model as usually understood (Volk et al., 2014; Thomson & Boehm, 2015). The fact is that an appropriate parametric model that is fit for purpose for a BIM-based process of design, construction and O&M of assets should incorporate geometrical and non-geometrical data (Sadeghineko & Kumar, 2020; Volk et al., 2014). In a BIM-enabled project, one of the main reasons behind the generation of a semantically enriched 3D model is to improve the information exchange and interoperability throughout the building's life-cycle (Curry et al., 2013). While the geometrical properties can be extracted from a PCD, non-geometrical data, such as O&M-related data (e.g. Residual Risks, Sustainability Performance, Expected Life, and Risks), may need to be appended to the 3D model for generating a genuinely semantically enriched 3D model. In current practice, approaches proposed and developed in the literature mainly focus on the detection of geometries in PCD rather than the information required in BIM models (Volk et al., 2014).

The Industry Foundation Classes (IFC) data model and the Construction Operation Building information exchange (COBie) data format are examples of information exchange standards within the AEC industry. COBie is a spreadsheet (.xlsx) data format that includes information about different aspects of an individual building, such as type, location, make, tag, serial number, and installation information of building elements. It is mainly used in AM/FM domains for O&M purposes and not for exchanging information between BIM-driven applications (Farias, Roxin, & Nicolle, 2015; Volk et al., 2014). The IFC data model, on the other hand, is an open-source data model developed by buildingSMART International (bSI). It is the most well known and commonly utilised information exchange standard between BIM-driven applications within the AEC industry (Pauwels et al., 2011; Kumar, 2016). However, due to some of the limitations and implications of IFC data model (Uggla & Horemuz, 2018; Molinero Sánchez, Gómez-Blanco Pontes, & Rivas López, 2019) on capturing all kinds of non-geometrical data, commercial BIM software largely suffer from the limitations of exchanging data and indirectly capturing semantically enriched 3D models of existing assets. In real-world projects, the information that cannot be appended to the BIM models is inevitably stored in different data formats outside the model which makes data manipulation, information exchange and interoperability processes ineffective and inefficient (Sadeghineko & Kumar, 2020).

Various schemas like ifcOWL (Pauwels & Terkaj, 2016), ifcJSON (Afsari, Eastman, & Castro-Lacouture, 2017), and COBieOWL (Farias et al., 2015) have been developed as a second alternative schema for distributing data on the Web effectively and efficiently by using semantic web technologies. However, they are not designed to generate BIM models and available BIM applications do not support such schemas currently (Volk et al., 2014; Sadeghineko & Kumar, 2020). For example, ifcOWL is predominantly created from an existing IFC data model by converting IFC into OWL (Web Ontology Language) ontology by the implementation of IFC-to-RDF (Pauwels et al., 2011) and EXPRESS-to-OWL (Pauwels & Terkaj, 2016) algorithms. The process of developing such schemas mainly commences from an existing building model, which may or may not incorporate geometrical and non-geometrical data. In terms of information exchange, different ontologies like Building Topology Ontology (BOT) and Ontology for Managing Geometry (OMG) have been developed by World Wide Web Consortium (W3C) Linked Building Data Community Group (W3C LBD-

CG) for storing and sharing data. BOT is a modular building ontology developed for expressing the topology of a building (e.g. Site, Building, Space, Building Element, etc.), and OMG has been developed for facilitating the reuse of linked geometry descriptions of an object on the Web (Rasmussen, Pauwels, et al., 2017; Terkaj, Schneider, & Pauwels, 2017).

An approach has been developed in Sadeghineko & Kumar, 2020 to address the challenges and limitations involved in generating BIM models from PCD. The proposed framework focuses on the generation of semantically enriched 3D retrofit models from PCD by utilising Resource Description Framework (RDF) as semantic web technology and standard. This paper outlines the proposed framework before proposing the approach for facilitating the information exchange for existing assets by utilising existing building ontologies.

2. Related work

2.1. Parametric modelling utilising Point Cloud Data (PCD)

An existing building may not have a 3D as-designed model or indeed any model at all. In such cases, 2D drawings and paper-based or digital documents are the only available information sources for generating BIM models (Sadeghineko et al., 2018; Sadeghineko, Kumar, & Chan, 2019). In this case, the procedure of generating BIM models is implemented through a Scan-to-BIMs process by directly utilising PCD as the primary geometrical data captured from an asset (Thomson & Boehm, 2015). PCD is widely used in the AEC industry to generate parametric models manually by using commercial BIM platforms. Therefore, various approaches have been proposed in the literature to move from the traditional and manual process of generating parametric models towards an efficient and effective automated or semi-automated procedure. Geometric attributes, such as linear, planar patches (surfaces), 3D primitives, and volumetric characteristics, are employed in proposed methods to declare automated or semi-automated procedures with varying success (Tran, Khoshelham, Kealy, & Díaz-Vilariño, 2018; Thomson & Boehm, 2015). The Scan-to-BIMs process is generally implemented through several steps, viz. the collection of data in the form of PCD, PCD registration, PCD segmentation, and the generation of building elements (Figure 1).

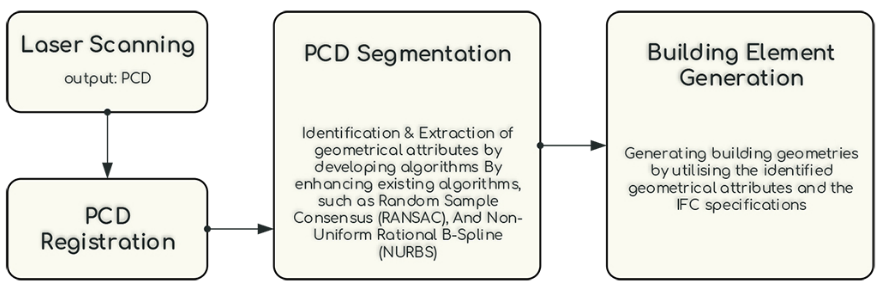

Fig. 1: The general process of capturing building elements from PCD, also known as Scan-to-BIMs.

The work carried out by Zhang, Vela, Karasev, & Brilakis, 2015 focus on the reconstruction of building elements in various real-world projects. Different data collection technologies, such as image- and range-based methods, are utilised to collect the data from existing buildings in the form of PCD. The main focus of this method is the identification of planar surfaces in the PCD due to the importance of planar patches in shaping 3D geometries and primitives (Dore & Murphy, 2015). A variety of different existing algorithms, such as unsupervised subspace learning technique, Maximum Likelihood Estimation Sample Consensus (MLESAC), Singular Value Decomposition (SVD) procedure, and α-shape algorithm, is utilised to generate building elements from PCD. These techniques are widely adopted in the computer science domains like image processing for extracting and classifying linear features embedded in collected data. A segmentation algorithm declared based on the unsupervised subspace technique is utilised to retrieve linear relationships between elements in PCD. This technique is employed to identify the number of linear relationships, associated dimensions, and segmentation groups of points in PCD. The MLESAC and SVD methods are then applied to calculate and extract plane models from the PCD. The α-shape algorithm is lastly used to extract the corresponding planar patches (surfaces) from the PCD as the final output of this approach. Another example of generating building elements through the Scan-to-BIMs process can be the work undertaken by Thomson & Boehm, 2015 focusing on the 3D documentation of building components like walls, floors, and ceilings. The PCD segmentation process is implemented through the RANSAC (RANdom Sample Consensus) algorithm, which results in the detection of planes and surfaces related to building components. The geometrical attributes, such as coordinate, width, and length, are then employed to construct the IFC entities for identified elements. The created IFC data model is then used to visualise the 3D geometries.

The use of BIM processes has also gained interest in retrofit and historical buildings. The work presented in Barazzetti, 2016 is an example of using PCD as the primary geometrical data source in the cultural heritage domain. A semi-automated approach is proposed to reconstruct different building components of various historical buildings by utilising NURBs (Non-Uniform Rational B-Splines) functions (Banfi, Chow, Ortiz, Ouimet, & Fai, 2018). A combination of range-based (e.g. Laser Scanning) and image-based (e.g. Photogrammetry) technologies is used to collect the data in the form of PCD. The discontinuity lines of targeted objects are first extracted from the collected data manually by considering NURBs attributes. Following this, control points, as one of the NURBs features, of extracted curves are utilised to form the surfaces semi-automatically. Generated surfaces as geometric constraints are employed to incorporate the external surface of the target element. The external surface is then used to generate solid geometries by extruding identified surfaces based on the required thickness. This approach is applied to different building elements like walls, vaults, and structural components. The fact is that the final results of approaches proposed based on the Scan-to-BIMs method are simple shapes or primitives that only contain geometrical data, such as length, width, area, and volume. However, as mentioned previously, the non-geometrical data needs to be appended to the 3D geometries through a manual process by either converting 3D geometries into building types (building elements/objects) where the non-geometrical data can be attached to the model or creating new building components based on the model specifications.

2.2. Information exchange within the AEC industry

One of the main reasons behind BIM-driven project delivery in the AEC industry is the storage, share, and reuse of information in the form of standard formats (Beetz & Borrmann, 2018; Kumar, 2016), and the objective is to improve the information exchange processes. One of the challenges in the AEC industry is the communication between different BIM platforms which directly impacts the information interoperability performance (Pauwels et al., 2011). Therefore, several open data exchange formats and schemas have been developed to represent the construction data and to enhance the communication between modelling applications and indeed, participants involved in a project. The IFC data model, as well as the Construction Operation Building information exchange (COBie) data format, are well-known and practical examples of data exchange standards within the AEC industry. COBie is an international data exchange standard predominantly used in AM/FM domain for information interoperability and O&M purposes (Shalabi & Turkan, 2016; Volk et al., 2014). However, the existing information exchange standards and formats also show limitations for certain functionalities. For example, COBie is essentially a non-geometrical data source mainly used for sharing the information about an individual building in the form of Excel spreadsheets and cannot be utilised in BIM-driven applications for generating BIM models (Farias et al., 2015; Gui, Wang, Qiu, Gui, & Deconinck, 2019). About the IFC data model, it is not capable of presenting all kinds of non-geometrical data, and commercial BIM applications largely suffer from the limitations of exchanging data and indirectly capturing 3D models of buildings, in particular, existing assets. Hence, some of the information that cannot be presented through the existing information exchange standards and formats is inevitably stored in different file formats, such as PDF, 2D paper-based CAD drawings, Excel spreadsheets etc. outside the model (Sadeghineko & Kumar, 2020).

The use of Semantic Web technologies and standards like web-based ontologies has gained notable interest within the AEC and AM/FM for information exchange, interoperability, and management. To address the challenges and limitations of existing information exchange standards studies have been undertaken to improve existing standards and tools by utilising Semantic Web technologies as a feasible solution. Some of the examples of these are the ontology for IFC, also known as ifcOWL (ifc Web Ontology Language), an ontology for COBie (COBieOWL), and ifcJSON (ifc JavaScript Object Notation). The main idea behind the development of new schemas is to use existing information about a building and convert it into OWL ontologies, which are predominantly used to store and share the information on the Web. While some of the studies focus on using Semantic Web technologies and standards to improve existing data exchange tools, others focus on the development of web-based ontologies to describe construction-related information. The Building Topology Ontology (BOT), Ontology for Managing Geometry (OMG), Building Product Ontology (BPO), and Bridge Topology Ontology (BROT) are examples for such ontologies.

2.3. Web-based ontologies for buildings

In terms of improving existing information exchange standards and tools, studies have been undertaken over the past years proposing web-based schemas by utilising Semantic Web technologies and standards. As mentioned previously, ifcOWL, ifcJSON, and COBieOWL are examples of such schemas. Concerning the ifcOWL schema, the first conversion of IFC schema into OWL was initially proposed by Schevers & Drogemuller, 2005. IFC data model was utilised as a reference example for highlighting and addressing some of the key issues of information exchange and interoperability within AEC. To enhance the applicability and reusability of the IFC data model, Beetz, Van Leeuwen, & De Vries, 2009 proposed a semi-automated approach focusing on the conversion of IFC-EXPRESS into OWL (ifcOWL). Thenceforward, studies have been carried out proposing Web Ontology versions of different IFC formats like OntoSTEP (Ontology for Standard for Exchange of Product data model) version proposed by (Barbau et al., 2012). However, there was a lack of formalisation and standardisation in proposed ontologies. Hence, a more usable and recommendable version of ifcOWL was developed by Pauwels & Terkaj, 2016. The current version of ifcOWL is initially developed by the implementation of IFC-to-RDF (Pauwels et al., 2011) and EXPRESS-to-OWL (Pauwels & Terkaj, 2016) procedures. The main idea behind the creation of ifcOWL was to continue using the IFC standard for the representation of building data and to take advantage of Semantic Web technologies for the distribution, extensibility and reasoning of data (Pauwels & Terkaj, 2016). However, despite the improvement that has been made to the original IFC data model through the use of Semantic Web technologies, ifcOWL also shows limitations in real-world project usage. As stated in (Terkaj & Pauwels, 2017), "*the resulting ifcOWL is a large monolithic ontology that presents serious limitations for real industrial applications in terms of usability and performance (i.e. querying and reasoning)*". In addition to that, in contrast to the original IFC data model, ifcOWL cannot be employed as an information exchange standard for the communication between BIM-driven applications as they do not support such schemas.

Another example of Semantic Web-based schema created for the IFC data model is the work presented in Afsari et al., 2017. The main objective of the proposed method is to provide the JSON (JavaScript Object Notation) representation of the IFC specification. Similar to the ifcOWL, ifcJSON uses the EXPRESS schema to present existing entities of IFC data model schema generated for an individual building project in the form of JSON syntax. The study carried out by Farias et al., 2015 proposes a semi-automated approach for creating the COBieOWL ontology by using the data presented in COBie spreadsheets. The generated COBieOWL is first serialised into RDF Turtle format and then edited in Protégé OWL editor before populating the data. The SPARQL query language is employed in Protégé to manage and manipulate the data presented in COBieOWL ontology. In terms of generating building models using the developed schemas, as mentioned previously, COBie is only used for information delivery of an individual asset in the AEC industry for maintenance purposes in the FM domain, and it cannot be used for generating models within BIM platforms. Moreover, the developed schemas mainly focus on using integrated information exchange standards and Semantic Web technologies to produce shareable data which can be a feasible solution to the information exchange and interoperability limitations within the building industry. However, the data used for implementing such schemas is extracted from an existing model. In fact, the model employed for creating shareable information may or may not incorporate all kinds of data that may be required for different sectors of a BIM process (Sadeghineko & Kumar, 2020).

While some of the studies focus on developing web-based schemas by improving existing information exchange and interoperability tools, some other studies focus on developing Web Ontologies for the representation of structured building data on the Web as Linked Data (LD) or Linked Open Data (LOD). In current practice, the exchange of information and its description come with different data formats, and the communication between them is predominantly through diverse file formats with an implicit relationship between them (Pauwels, McGlinn, Törmä, & Beetz, 2018). However, the concepts of LD/LOD can be a feasible solution to the limitations that hamper appropriate communication between diverse data sources within the AEC industry. The main idea behind the LD/LOD is to use Semantic Web technologies and to combine data distributed in different data formats for enhancing the data interoperability, reasoning, and querying (Lee, Chi, Wang, Wang, & Park, 2016). Moreover, LD is a web-centric approach which provides a mechanism for gathering heterogeneous data formats and presenting them in the form of a homogeneous format. LD uses Semantic Web standards like RDF and OWL as its main structure, i.e. any type and format of data can be combined with LD from other domains as long as they use linked data standards (Curry et al., 2013). Nevertheless, studies have recently been carried out proposing Web ontologies, such as BOT, OMG, BROT, and BPO, for describing building data.

2.4. AEC domain ontologies

The Building Topology Ontology (BOT) as a minimal ontology was initially proposed and developed by W3C LBD CG (World Wide Web Consortium Linked Building Data Community Group). The general idea behind the creation of BOT ontology is to define the relationships between the sub-components of a building in a clear and detailed manner. It also aims to provide the method for the representation and reuse of information within the AEC industry in the form of interlinked data (Bonduel, Oraskari, Pauwels, Vergauwen, & Klein, 2018). The first version of BOT ontology was initially proposed in Rasmussen, Hviid, & Karlshøj, 2017, and an updated version of this ontology was presented in Rasmussen, Pauwels, et al., 2017 introducing changes applied to the initial version of BOT. Moreover, the definition of terms used in BOT ontology is identified by URIs (Uniform Resource Identifiers) in the BOT namespace (http://w3id.org/bot#). The prefix bot: is the shortened version of the BOT namespace (@prefix bot: <http://w3id.org/bot#>). The current version of BOT encompasses seven classes (e.g., bot:Zone, bot:Site, bot:Building, etc.), fourteen object properties (e.g., bot:containsZone, bot:hasBuilding, etc.), and one data property (bot:hasSimple3DModel). BOT documentation can be accessed through its IRI (Internationalised Resource Identifier) – http://w3id.org/bot. In addition, the building product, related properties and geometry ontologies are considered as the sub-groups of BOT ontology which is considered as the central and modular ontology. In other words, BOT ontology can be extended by other domain ontologies (Pauwels et al., 2018).

The Ontology for Managing Geometry (OMG) was initially proposed in 2019 by Wagner, Bonduel, Pauwels, & Uwe, 2019 to describe geometries related to building elements. In other words, OMG ontology focuses on providing the means for linking building objects data to their corresponding geometry descriptions. The OMG ontology documentation can be accessed through its IRI – http://w3id.org/omg. The URIs identify the terms in OMG ontology in the OMG namespace (http://w3id.org/omg#). Concerning the OMG specifications, an object can be linked to its geometry description through three modelling complexity levels with different levels of functionalities associated with each level. Level 1 provides the means for connecting objects to their geometry descriptions directly. Level 2 of OMG introduces additional functionalities to the model, viz. handling of multiple geometry descriptions of the same objects, adding metadata to the model, and modelling dependencies between geometries. The geometry states as additional functionality, i.e. the version history of the description of geometries, can be included in the model through the use of Level 3 of OMG ontology.

The Building Product Ontology (BPO) (Wagner & Rüppel, 2019) is a minimal ontology designed for describing some of the non-geometrical data, predominantly assembly structures, relationships and connections between product components, properties, and property values, related to their corresponding building products and elements. However, BPO ontology does not support the representation of geometrical descriptions and material compositions of building products. Similar to other ontologies, BPO contains several classes, object properties and datatype properties utilised for representing building product descriptions. More information about BPO documentation can be found through its IRI – http://www.w3id.org/bpo. In terms of the topological and geometrical representation of building products, BPO can be extended and combined with BOT, OMG, and indeed other ontologies to enhance the information exchange process about building projects. Several other ontologies are available within the AEC domain, which can be used to represent different building-related data like Smart Energy Aware Systems (SEAS) ontology and Bridge Topology Ontology (BROT). However, BOT, OMG, and BPO ontologies are specifically used to extend the ontology created for the proposed approach, which is described in the following sections.

3. A framework for generating semantically enriched retrofit 3D models using RDF

An appropriate parametric model that is fit for the BIM process of design, construction and O&M of buildings should incorporate geometrical and non-geometrical data. In current practice, the model generated from PCD initially contains only geometric data. The non-geometrical data needs to be appended to generated geometries in order to capture BIM objects that incorporate geometrical and non-geometrical data. BIM applications and related standards and tools like IFC are not capable of representing all kinds of data. Due to these limitations of the data is stored in different data formats, which makes the process of data manipulation, management, and indeed information exchange and interoperability inefficient and difficult. Hence, a framework has been developed in Sadeghineko & Kumar, 2020, which focuses on addressing challenges and limitations involved in generating semantically enriched 3D retrofit models. As shown in Figure 2, the framework consists of three key steps, viz. 1) data collection, 2) data processing and 3) BIM models generation.

The data collection step focuses on assembling geometric and non-geometric data. The geometrical data such as Cartesian points (coordinates) and geometric properties (e.g., length, width, and height) are extracted from the geometries identified in PCD. In addition, offline and online data sources are used to collect the non-geometrical data. In current practice, the non-geometrical data are stored as offline and/or online data in different formats. These data sources are used to retrieve the required non-geometrical data presented in different data formats. In the data processing step, the collected data is first aggregated into a unified data format. The Resource Description Framework (RDF) as a Semantic Web standard and technology is used as the unified data format to aggregate data collected from distributed data formats. In terms of utilising RDF data to generate BIM models, data presented in RDF is classified into two different sections, viz. IFC and Non-IFC Compliant Data.

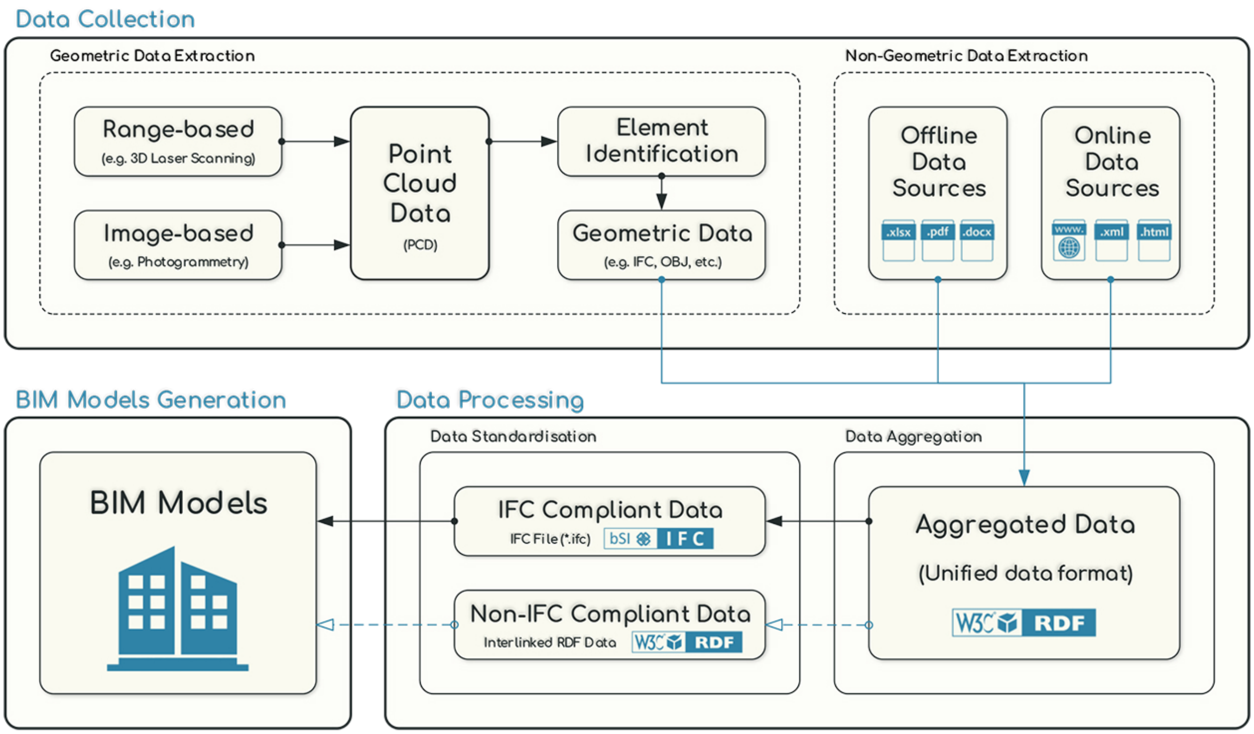

Fig. 2: A framework for generating semantically enriched 3D retrofit models.

As previously mentioned, the IFC data model as the commonly used standard tool for exchanging building information within the construction industry is not capable of handling all kinds of non-geometrical data. Hence, the first section includes data that is compliant with the IFC data model specifications and can be combined with the BIM models through the IFC format directly. The latter section contains data, predominantly a considerable portion of non-geometrical data, that cannot be combined with the model through the IFC. This portion of data remains in the form of RDF data which is interlinked with the model. The structure of an RDF statement is based on three parts, also known as triples, including a subject, predicate, and an object. The subject and predicate are declared as Uniform Resource Identifiers (URIs), and the object can be declared either as a URI or a literal value. URIs provided in the model are used as links to the information associated with BIM objects. Moreover, non-IFC-compliant data can be accessed through these links by importing the IFC file into any BIM platform that supports this format or by opening the model generated from the IFC file in BIM applications such as Revit, BIM 360, and Autodesk A360 platforms. The implementation of an RDF-TO-IFC algorithm carries out the process of generating semantically enriched 3D retrofit models from RDF data.

Furthermore, in terms of scalability and replicability, the developed framework is not limited to a specific building type and can be applied to any type of building, including new, existing and retrofit assets. The geometrical and non-geometrical data of an existing building was used to validate the process of the framework. The building project includes multiple wall components, slabs, door and window openings distributed in two floor plans. RDF data generated for each individual building element was utilised to implement the RDF-TO-IFC algorithm for creating the IFC file. The IFC file was then employed to generate the model in BIM applications that support this format. Figure 3 illustrates the generated model opened in Autodesk BIM 360 environment as well as the RDF data links associated with their corresponding building objects. These links are utilised as linked data to access the information related to each component. Figure 3 also shows the data related to a wall object presented on the web that is accessed via the live links provided in the model. One of the major advantages of the developed framework is that any type of data, including geometrical and non-geometrical data, can be combined with the model as an interlinked data and the RDF data can also be used as Linked Data (LD) to other data that is structured based on RDF specifications, such as ifcOWL and OWL ontologies. Moreover, the availability of geometrical and non-geometrical data in the form of a standard and unified data format improves the information exchange and interoperability in BIM-enabled projects.

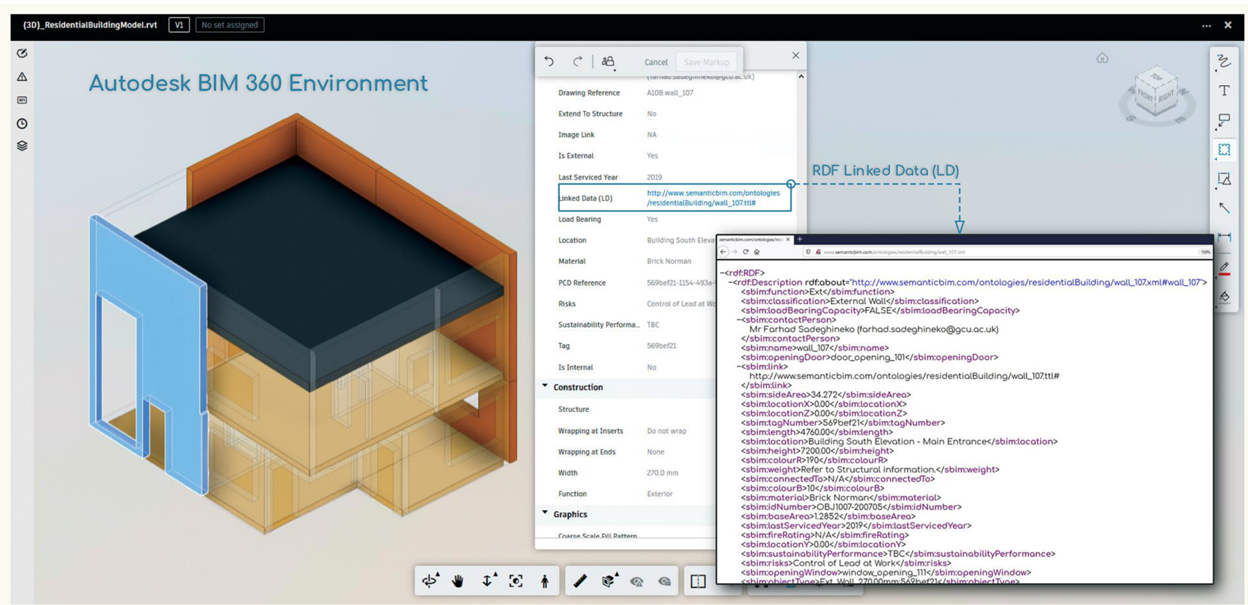

Fig. 3: BIM model opened in Autodesk BIM 360 environment and links that are appended to the model to access data associated with building objects.

4. Facilitating information exchange and interoperability for existing assets

A reliable data format – data unified in a single standard format – which is capable of handling all kinds of data is crucial in the exchange and interoperability of digital building data within the construction industry. In terms of the exchange and interoperability of information, Semantic Web technologies, in particular ontologies, have been used to provide feasible solutions to the challenges and limitations involved in the exchange of construction-related data. The proposal and use of data exchange frameworks that are designed and structured based on the Linked Data (LD) principles can be a promising approach for combining distributed data. An LD-based structure can subsequently provide the opportunity for improving the information exchange processes between stakeholders engaged in construction projects. Concerning the framework described in the previous section, simple RDF data has been used as the single standard and unified data format to aggregate distributed offline and online data, including geometric and non-geometric data. In terms of simplifying the translation process of RDF into IFC, the applicability of RDF specifications has been utilised to create RDF graphs associated to their corresponding building objects, such as site, building, building storey, slabs, internal and external walls, window and door openings. As stated in Sadeghineko & Kumar, 2020, the developed framework was instigated by a partnership between Historic Environment Scotland (HES) and the authors' institution. With respect to the HES BIM project (Sadeghineko & Kumar, 2020), the provided data has been utilised to structure and generate RDF graphs.

However, this paper proposes an approach which aims to facilitate the information exchange and interoperability for

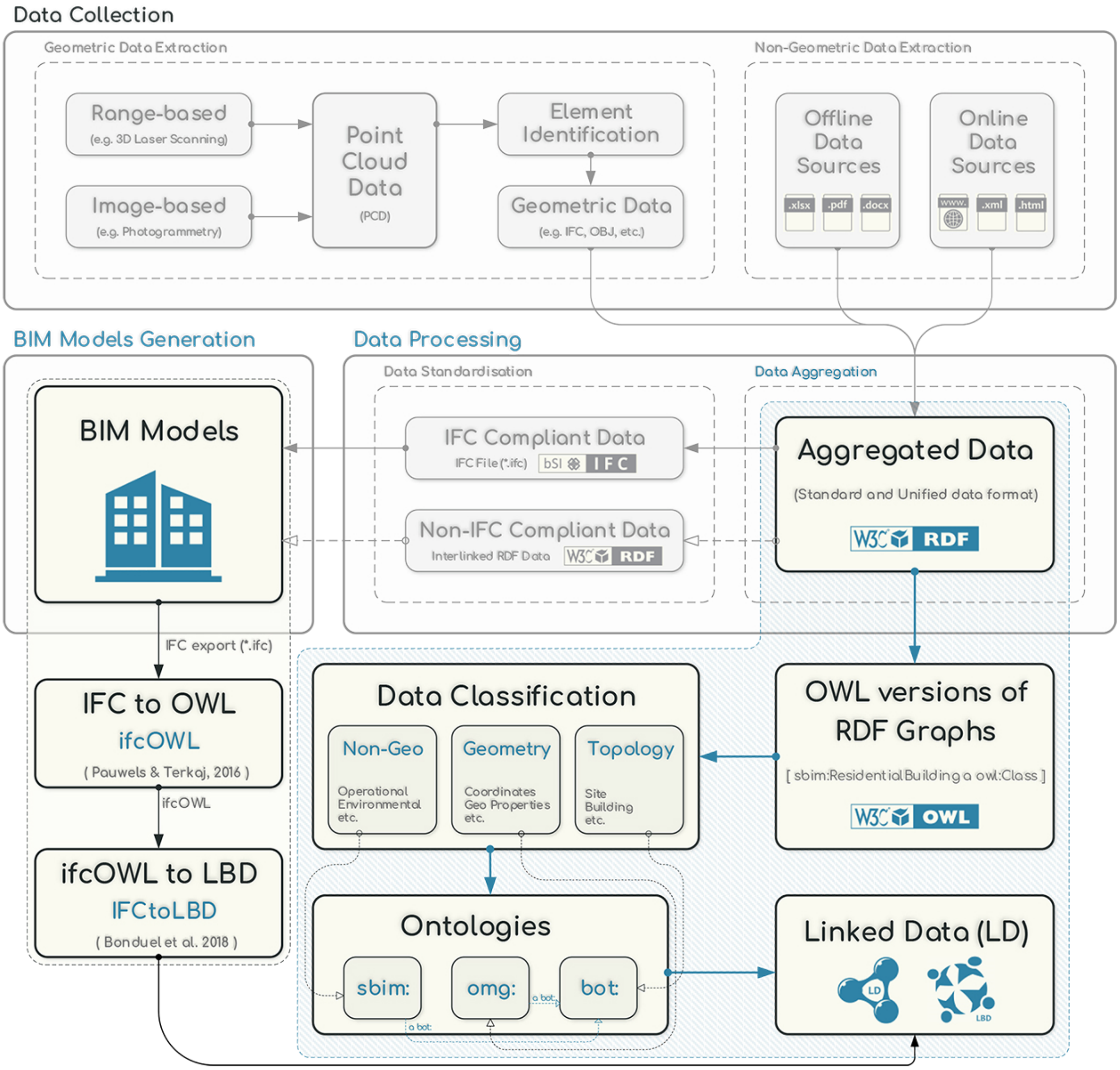

Fig. 4: The Proposed approach for facilitating information exchange and interoperability for existing assets.

existing assets through the use of Semantic Web technologies, including RDF data and minimal ontologies developed within the building environment. The general workflow of the proposed approach is illustrated in Figure 4. First, an OWL version of the data presented in generated RDF data (graphs) is created in order to be able to use data presented in RDF graphs as extended and linked data to other ontologies. Data presented in RDF graphs are classified into three key categories which include Topological, geometrical, and non-geometrical data. The topological category includes data that represent spatial relations about building components. The geometrical data contains geometric properties related to their corresponding building elements. The remaining data, such as operational and environmental data, are presented in the category of non-geometrical data.

The example application used in this paper is about the data of a two-storey residential building which was initially generated through the use of data presented in the form of RDF graphs and the translations of graphs into IFC data model (see Section 3). Different ontologies have been adopted to create the ontology associated with the above-mentioned data. Some of these ontologies have been imported directly into the base ontology in order to use their applicabilities. On the other hand, there are also other ontologies which are imported into the base ontology indirectly through the import of the first group of ontologies. The namespaces and prefixes of multiple web ontologies that are used in this paper are listed in Table 1. Nevertheless, from a topological perspective, the applicability of BOT ontology can be used to represent the spatial relationships between building elements like zone, site, building, etc. Hence, the proposed framework in this paper uses the BOT ontology to describe the spatial connections and relationships between the elements in the example application. The geometrical data mainly concerns the questions about the shape, size, relative position of objects, and indeed their corresponding properties like length, width, height, etc. The applicability of OMG ontology has been utilised to describe the geometrical representation of building elements.

Table 1: Namespaces and prefixes of the referenced web ontologies and imported ontologies.

Prefixes	Name	Domain
bot	Building Topology Ontology	https://w3id.org/bot#
bpo	Building Product Ontology	https://w3id.org/bpo#
omg	Ontology for Managing Geometry	https://w3id.org/omg#
owl	Web Ontology Language	http://www.w3.org/2002/07/owl#
rdf	Resource Description Framework	http://www.w3.org/1999/02/22-rdf-syntax-ns#
xml	xml	http://www.w3.org/XML/1998/namespace
xsd	xsd	http://www.w3.org/2001/XMLSchema#
foaf	foaf	http://xmlns.com/foaf/0.1/
rdfs	Resource Description Framework Schema	http://www.w3.org/2000/01/rdf-schema#
sbim	sbim	http://www.semanticbim.com/ontologies/residentialBuilding.owl#
seas	Smart Energy Aware Systems Ontology	https://w3id.org/seas/
vann	vann	http://purl.org/vocab/vann/
voaf	voaf	http://purl.org/vocommons/voaf#
terms	terms	http://purl.org/dc/terms/
schema	schema	http://schema.org/
qudt	Quantities, Units, Dimensions and Type Catalog	http://qudt.org/schema/qudt

Moreover, a graphical view of the topological relationships between building elements and their geometrical descriptions is illustrated in Figure 5. The instance (owl:NamedIndividual) sbim:Site_G1 is defined as an instance of the bot:Site class, which is a subclass of the bot:Zone class. The sbim:Site_G1 instance is then linked to sbim:Building_G1 as a bot:Building class instance through the bot:hasBuilding object property. The sbim:Level_1 as a bot:Storey instance is linked to the sbim:Building_G1 instance by the bot:hasStorey object property. The relationships between the building instance and its corresponding elements are defined by the bot:Element class and related object properties. However, the geometrical description of instances is described through the OMG ontology. For example, the sbim:length as an omg:Geometry instance is a geometrical description of the sbim:wall_107 instance which is linked to the sbim:wall_107 instance through the omg:hasGeometry object property.

However, existing ontologies, such as previously described ontologies, are designed based on specific functionalities (e.g. topology, geometry, property management, etc.) and may not be able to support all kinds of data. Hence, depending on the nature of the example application project, new classes, object properties and data properties have been defined in the base ontology to provide fundamentals for describing all data that is represented in RDF graphs. As shown in Figure 6, the sbim:Project class has been created to describe geometrical and non-geometrical information by using previously mentioned ontologies and new entries. For instance, while the coordinate for the project origin point and the spatial dimensions of the BIM model is described by using the OMG ontology specifications, other associated information like the phase of the project (sbim:projectPhase as an instance of sbim:Project is described through the use of new classes, object & data properties (e.g., sbim:hasPhase as an owl:ObjectProperty and sbim:hasLiteralValue as an owl:DatatypeProperty) which are specifically defined for this project.

Other ontologies like Building Product Ontology (BPO) (Wagner et al., 2019) can also be used to extend the ontology created for the example application in order to enhance the applicability of the data exchange process. The BPO ontology is a minimal ontology aiming to describe a schematic representation of building products. In this regard, BPO ontology is used in the proposed approach to describe the building components and their corresponding relationships and connections. As an example of the use of BPO ontology, following the wall and door opening instances illustrated in Figure 5, the inclusion of a door component data through the use of BPO ontology is accordingly shown in Figure 7.

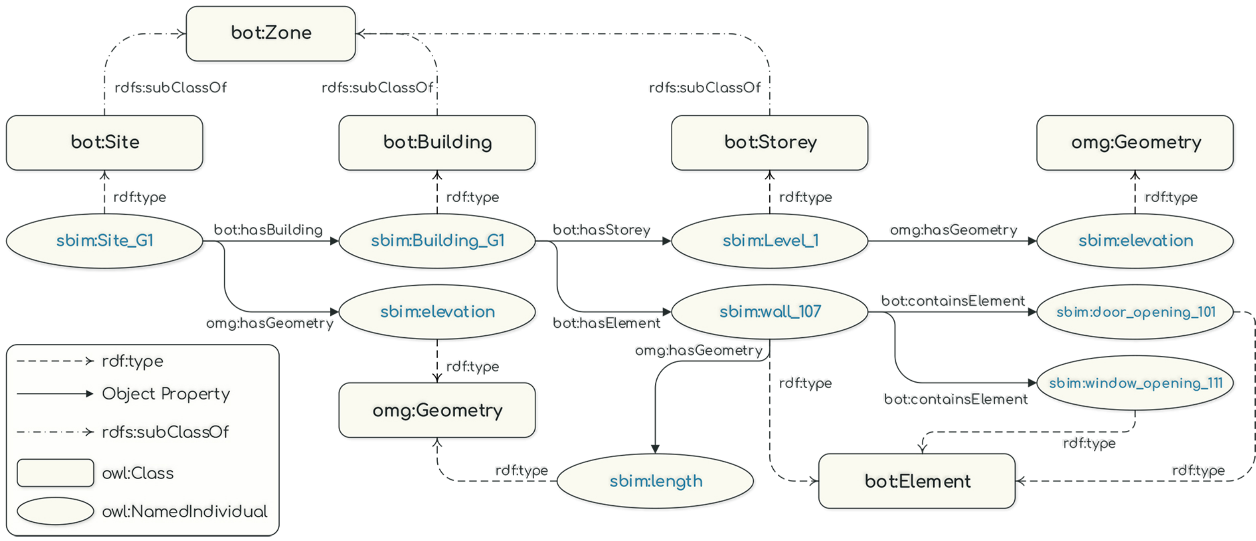

Fig. 5: Topological and geometrical relationships between building elements by using BOT and OMG ontologies.

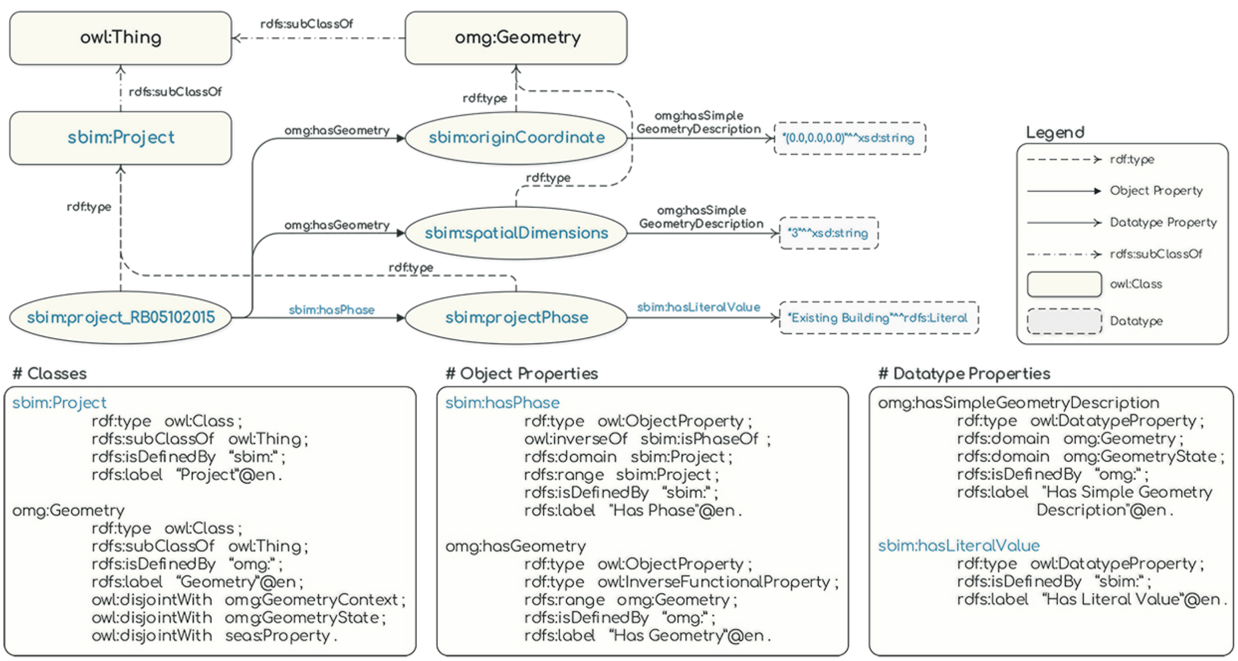

Fig. 6: The relationships between sbim classes and instances and imported ontologies.

Moreover, the material of building elements and components is consequently described through the sbim:NonGeometry class, sbim:Material instance and sbim:hasMaterial object property defined in the base ontology.

The created ontology as the final output of the proposed approach can be used as LD to other domains like Linked Building Data (LBD). As shown in Figure 4, the other capability of the proposed approach is that the information associated with the BIM model can be exported as an IFC data model, and converted into its ifcOWL version through the implementation of IFC-to-RDF (Pauwels et al., 2011) and EXPRESS-to-OWL (Pauwels & Terkaj, 2016) algorithms. The ifcOWL version can subsequently be converted to LBD through the IFC-to-LBD procedure developed by Bonduel et al., 2018. The LBD data can then be used as LD to other domains, including the ontology created for the example application in this paper, for further data exchange purposes.

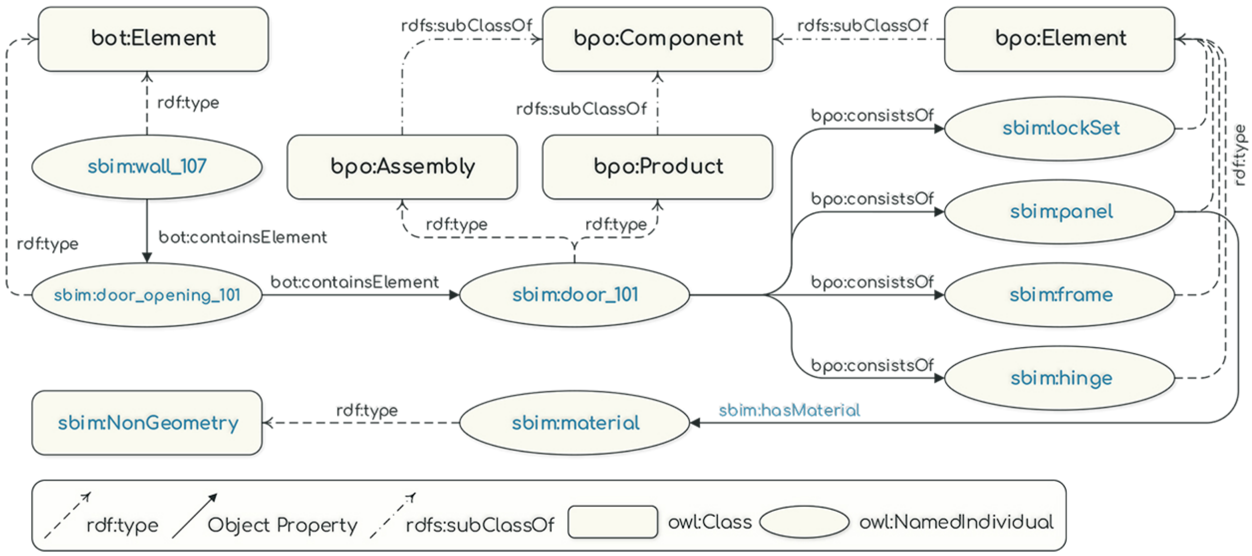

Fig. 7: The description of a door component using BPO ontology.

5. Conclusion

The framework proposed in this paper focuses on facilitating the information exchange and interoperability for existing buildings by using Semantic Web standards and technologies. The framework aims to use previously RDF graphs generated for building elements through the process of aggregating geometric and non-geometric data. As described in Section 3, the data was used to generate BIM models by the translation of RDF into IFC data model. However, the approach presented in this paper focuses on the creation of a web ontology from the data represented in RDF graphs by using the applicability of existing ontologies within the AEC industry. Each of the existing ontologies focuses on particular concepts, e.g. the BOT ontology concerns with the description of topological connections and spatial relationships between building elements without describing geometrical or non-geometrical data. However, one of the advantages of using web ontologies for storing, sharing, and reusing data is that ontologies can easily be extended and linked to other data sources which are structured based on OWL specifications. Moreover, new classes, sub-classes, object and datatype properties can be included in an ontology where required.

The approach presented in this paper is a solution to the challenges and limitations involved in generating semantically enriched 3D retrofit models for existing assets as well as the information exchange and interoperability within the AEC industry. The use of Semantic Web technologies, in particular RDF and OWL, facilitates data management by simplifying the data storage, share, and reuse. It also represents high-quality connected data and provides the basics for publishing linked data. The developed framework contributes to Asset/Facilities Management (AM/FM) and could be beneficial for a variety of AM/FM practices for existing buildings, including a consistent and computable building information/knowledge management for design, construction and O&M of a building's life-cycle, the effectiveness and efficiency of the use of project information during the O&M of facilities, and prompt problem detection and resolution. It can also contribute to other trends related to the information exchange and interoperability like the emergence of the Internet of Things (IoT) in smart buildings, building automation & monitoring, and building-related Information Technology (IT) infrastructure.

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